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Permanent Magnet Synchronous Generator Performance in Wind Turbine Systems

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ABSTRACT: This paper describes the performance comparison of a wind power systems based on permanent magnet synchronous generators as well as the experimental demonstration of a wind turbine simulator for the maximum power extraction. The techniques of direct grid integration, independent power control, and the droop phenomenon of distribution line are studied. System is modeled in Matlab/Simulink environment, and the operation is tested for the wind turbine maximum power extraction algorithm results.

KEYWORDS: permanent magnet synchronous generators, field-oriented control, maximum power tracking, wind power system.

I. INTRODUCTION

Renewable energy such as wind power is an important solution to reducing carbon emissions. Nowadays, with the rapid development of wind power technology, wind power can be converted into a useful form of energy, such as using wind turbines—the device that converts kinetic energy from the wind—to make electrical power. In fact, since wind power, as an alternative to fossil fuels, produces no greenhouse gas emissions during operation, it makes a huge difference to our environmental impact. Despite very significant advancements and influence to the environment, wind power costs continue to be greater than the existing low-carbon alternative such as natural gas. Therefore, much research remains to be done in order to improve wind turbines' behaviour and to make them cost-efficient to compete with the traditional energy such as natural gas.

There are many kinds of variable speed generators used for wind turbine. According to the reference [1, 2], although doubly fed induction generator (DFIG) is more broadly used than permanent magnetic synchronous generator (PMSG) today, PMSG has some advantages which are counted as experts. Particularly, PMSG is direct drive, has slow rotation speed, does not have rotor current, and can be used without gearbox. The high efficiency and low maintenance will reduce the cost that is the most concern to invest. However, PMSG still has some drawbacks. It needs electromagnetic field with the flexible structure, which leads to the high standard of the production as well as of the operation. Furthermore, variable speed of the generator has to be known by power inverter too.

According to the continuous development of wind power technology, the efficiency of inverter device, facing some tough issues, plays an important role in the improvement of wind power generation system performance. They need to be enhanced by novel controller [3] to improve the efficiency and the reliability. Inside them, MPPT integrating with the back to back space vector PWM [4] is the advantage control novel in [5–8], which is used to measure the rotor speed and compare with the calculated optimal rotor speed. On the other hand, not only does the inverter take an advantage in efficiency control but also the pitch angle controller takes another important part of wind turbine. It is integrated to adjust the aerodynamic torque of the wind turbine when this study rates wind speed.

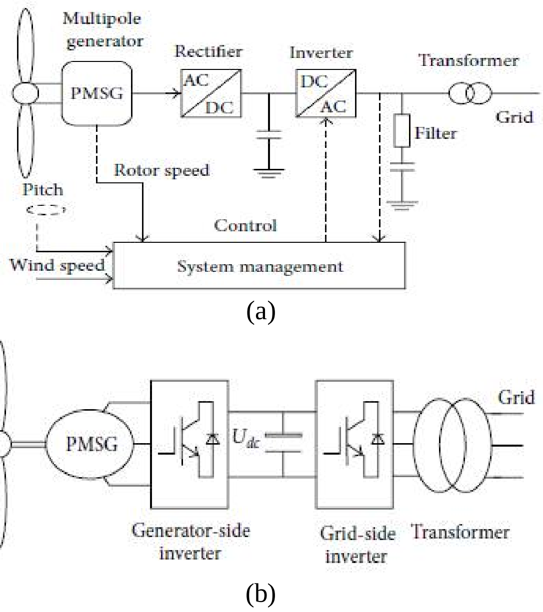

Figure 1: General wind turbine PMSG system with control schemes (a) and (b).

This study will model the whole wind turbine system including physical part of permanent magnet synchronous generator and control strategies for generator side and grid side as well as the pitch angle controller to depict the effects and the efficiency of PMSG by autonomous controllers. The model system and control strategies contain a PMSG wind turbine model, a pitch angle control model, generator-side inverter control model, and grid-side inverter control model.
The generator-side inverter and grid-side inverter controller adopt the back to back space vector PWM to enhance the performance of MPPT as well as decoupling control of the active and reactive power by adjusting the current of d-axis and q-axis of their side inverters. Furthermore, conventional PI controller is also used to improve the control strategy.
It is integrated in generator-side inverter, grid-side inverter, and the pitch angle controller. Matlab Simulink 2012b as reference [9] is conducted to simulate and demonstrate the performance. The results will demonstrate the effects and the efficiency of PMSG wind turbine which is integrated by autonomous controllers.

II. MODEL OF PMSG WIND TURBINE

A. STRUCTURE OF PMSG WIND TURBINE

The basic of PMSG wind turbine structure shown on Figure 1 is defined as [10]. The wind turbine generates torque from wind power. The torque is transferred through the generator shaft to the rotor of the generator.The generator produces an electrical torque, and the difference between the mechanical torque from the wind turbine and the electrical torque from the generator determines whether the mechanical system accelerates, decelerates, or remains at constant speed.
The generator is connected to a three-phase inverter which rectifies the current from the generator to charge a DC-link Udc capacitor [11]. The DC-link Udc feeds a second three-phase inverter which is connected to the grid through a transformer. Through the control system, the information of wind speed, pitch angel, rotor RPM, and inverter output is accepted to compare with the grid-side data. Therefore, this information is solved by using a digital signal processing system to produce the correct signal to control these components.
The main goal is to synchronize with utility grid and to export power to it.

B. MODEL OF WIND TURBINE

The wind turbine is used of the conversion of wind kinetic energy to mechanical work. On the basis of relationships for the calculation, it is possible to express the value P□ of the aerodynamic wind turbine power:

$$Pm = 0.5 \cdot \rho \cdot A \cdot V3 \cdot Cp\,(\lambda, \beta)\,.\ (1)$$

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Here, ρ is the air density, $A = \pi \cdot R$ 2 is the blades swept of the turbine, V is wind speed, and $Cp(\lambda, \beta)$ is the power coefficient, which expresses the relationship between the tip speed ratio λ and the pitch angle β.
The power coefficient (λ, β) is as

Cp (λ, β) = 0.22 (116/□− 0.4 . β − 5) . exp (−12.5/□), (2)

with
1/□ = 1/(λ + 0.089)−0.035(β3 + 1). (3)
The relationship between the wind speed and the rotor speed is defined as tip speed ration λ:
λ =R . w/V, (4)
where w is the blades angular velocity and R is the rotor radius.
From the value of the rotational motion performance, it is possible to determine the value of the torque □□ acting on the shaft as follow:
□□ =P□/w. (5)
These formulas are evident that the instantaneous values of the performance, respectively, of the mechanical torque, Mathematical Problems in Engineering 3

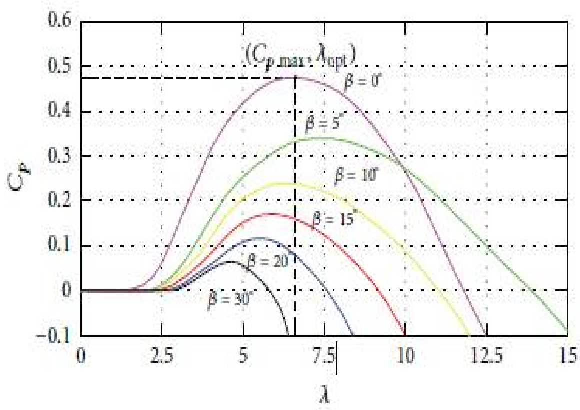

Figure 2: The curve of power wind turbine coefficient.

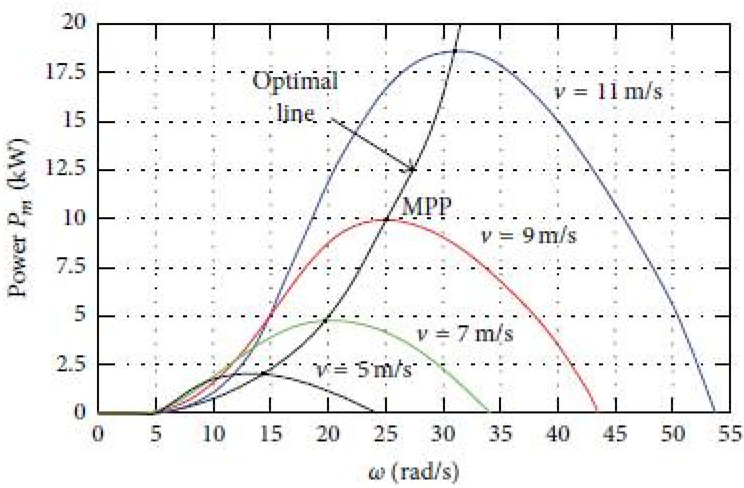

Figure 3:Thecurve to illustrate the relationship between power and wind speed.

are dependent on the wind speed very much. On the basis of these equations, it is possible to build the model, which structure is shown in Figure 4, of the wind turbine in Simulink platform.
Figure 2 shows the curve of power wind turbine coefficient. It reveals that Cp achieves the maximum value at the particular λ opt.

Figure 3 shows that the rotational speed is a function, in which the power captured in turbine blade obtains the maximum output at the particular rotational speed, while the pitch angle is constant Hence, λ should be kept at λ opt to maximize the wind energy.

In Figure 4, f(u) of Lambda, Gama, and Cp are defined in the order of equations (4), (3), and (2). If wind speed is in the range from3m/s to cut out 25m/s, it is combined to form turbine torque f(u) as (1) and (5).

2.3. Model of Permanent Magnet Synchronous Generator

The generator model is implemented entirely in dq-coordinates. It means that there are no AC-states in the model. The generator is modelled with DC voltages and currents in a rotor-fixed rotating coordinate system which is illustrated in Figure 5.

The equations for the d-axis and q-axis currents are defined in [1–3] as

$$\frac{di_{sd}}{dt} = -\frac{R_{sa}}{L_{sd}} i_{sd} + \omega_s \frac{L_{sq}}{L_{sd}} i_{sq} + \frac{1}{L_{sd}} u_{sd}$$

$$\frac{di_{sq}}{dt} = -\frac{R_{sa}}{L_{sq}} i_{sq} - \omega_s \left(\frac{L_{sd}}{L_{sq}} i_{sd} + \frac{1}{L_{sq}} \psi_P \right) + \frac{1}{L_{sq}} u_{sq} \quad .(6)$$

The equation of the electromagnetic torque in the rotor is

$$T_e = 1.5 \frac{P}{2} \left[\psi_P i_{sq} + i_{sd} i_{sq} \left(L_{sd} - L_{sq} \right) \right] \quad . (7)$$

There, isd, isq, usd, and usq are the d-axis and q-axis currents and voltages respective stator resistance; ws is the basic electrical angular frequency of the generator; Lsd and Lsq are the inductance of generator; Ψp is permanent flux; Rsa is the resistance of stator; and P is the number of poles.

Figure 5 shows the dq-coordinates frame of the PMSG with θ being the angle between d-axis and the main stator axis.

III. AUTONOMOUS CONTROL OF PMSG WIND TURBINE

A. GENERATOR-SIDE INVERTER CONTROLLER

The generator-side inverter is controlled to catch maximum power from available wind power. According to (7), in order to control the electromagnetic torque Te, this study just controls the q-axis current isq with the assumption that the d-axis current isd is equal to zero. Furthermore, [3, 14] showthat, in order to catch maximum power, the optimum value of the rotation speed is adjusted. The tip speed ratio λ is taken into account due to the equation being addressed as follow:

wref = λopt . VR. (8)

There,ref is the blades angular velocity reference and λopt is the tip speed ratio optimum.

From (6), it is calculated that

Usd = Rsa . isd − ws . Lsq . isq + disd / dt . Lsd

Usq = Rsa . isq + ws . Lsd . isd + disq / dt . Lsq + Es, (9)

with Es = ws . Ψp being the permanent flux linkages.

The generator-side inverter control schematic is illustrated in Figure 6. Through the MPPT in [5], the error of wref is produced. Therefore, the error of wref and ws is rescued toPI controller to produce q-axis current component isq ref which put into space vector pulse width modulation (SVPWM).The d-axis current isd ref is set to zero because the d-axis current control is adopted. Consequently, through the SVPWM containing voltage feed-forward compensation, the power factors of the generator are calculated and controlled well.

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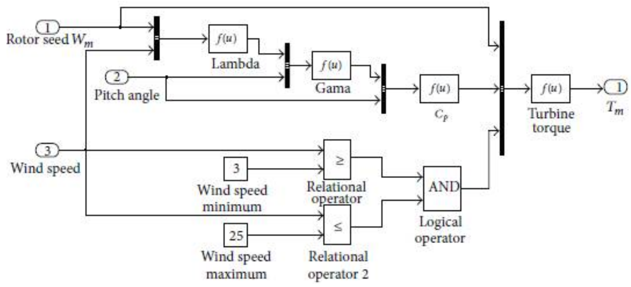

Figure 4: Model of the aerodynamic of wind turbine in Matlab Simulink 2010b.

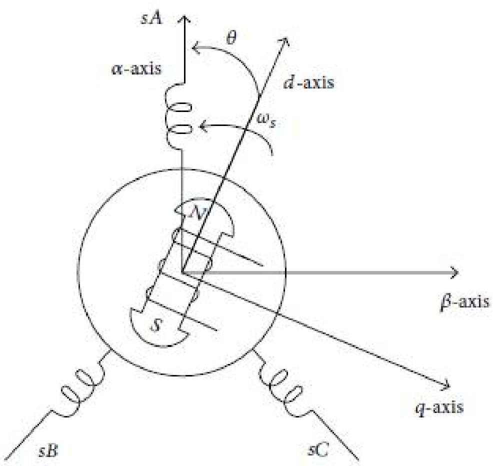

Figure 5: The dq-coordinate frame of the PMSG.

B. GRID-SIDE INVERTER CONTROLLER

The goal of the grid-side inverter is keeping the stability of the DC-line voltage as well as controlling the active and reactive power [3, 19].

For the grid/transformer inductance, the model is given as follows:

$$ud = ed - R \,.\, id + w \,.\, L \,.\, iq - L \,.\, did / dt,$$
$$uq = -R.\, iq - w \,.\, L \,.\, id - L \,.diq / dt. (10)$$

Here, ed is the d-axis output voltage of the grid, respectively, w is the angular frequency in electrical degree of grid, R is the resistance, L is the inductance, respectively, and id and iq are the currents of d-axis and q-axis. By (10), it is easy to figure out that the current of d-axis and q-axis can be controlled to moderate the active and reactive power. In Figure 7, the loop voltage and the loop current are illustrated. The inner current loop is controlled through PI controller similar to generator side inverter controller. The output voltage loop produces PI controller for calculating the error between Udc and Udc ref to produce id ref. Therefore, q-axis current is set to be zero to decoupling control of the active power P and reactive power Q by moderating the d-axis current id and the q-axis current iq.

C. PITCH ANGLE CONTROLLER

The system of aerodynamic control plays an important role in regulating the mechanical power. Pitch angle controller is based on the principle which is changing the blades angle at the revolutions over the maximal generator speed as well as protecting the generator before overloading at high wind speeds. The optimal angle for the wind speed below the nominal value is approximately zero and then it increases with the wind speed growing. It has considerable impact on the performance coefficient and on the value of the turbine torque.

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In this controller, illustrated in Figure 8, the speed of the generator which is the input is compared with its reference value through PI controller to have the output value of the pitch angle of the blades, which changes the performance coefficient of the turbine.

D. MAXIMUM POWER POINT TRACKING (MPPT)

In the generator-side inverter, MPPT produces the wref for the comparative PI controller. According to Figure 3 and [5–8], the wind turbine coefficient achieves the maximum for the tip speed, when the pitch angle $\beta = 0$. In terms of every wind speed, there exists a specific point to get the maximum output. Hence, in order to control the maximum power in every wind speed, the MPPT tracks the continuous line and optimal line in Figure 9.

The tip speed ratio is kept at constant value for all maximum power points, while the relationship between the wind speed and the wind turbine generator speed is explained as follows:

$$\Omega n = \lambda n\ Vn/R, \quad (11)$$

with Ωn being the optimal rotation wind turbine generator at the wind speed Vn.

The MPPT control strategy is based on monitoring the wind turbine generator output power using measurements of the wind turbine generator output voltage and current as well

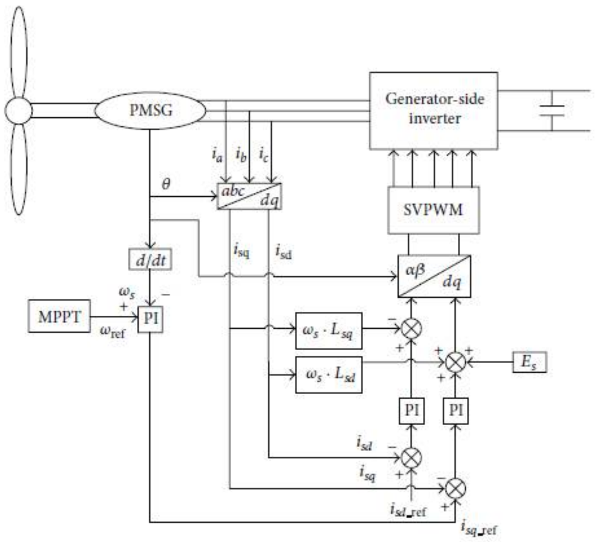

Figure 6: Scheme of generator-side inverter controller.

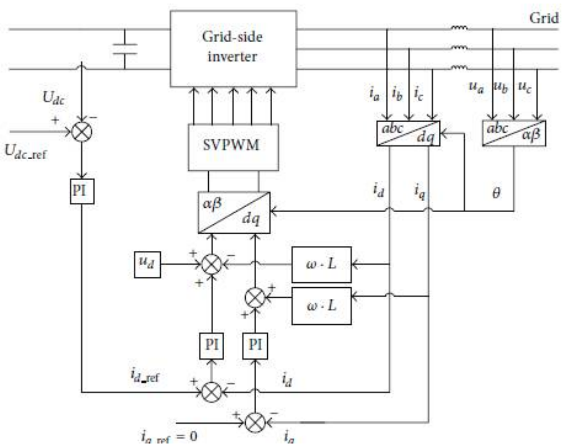

Figure 7: Scheme of grid-side inverter controller.

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as directly modelling the dc/dc converter duty cycle, which is followed by the comparison of among output power values.

IV. SIMULATION ANALYSIS

In order to verify themodel of the whole autonomous control system design, Matlab 2010b is used to simulate this system design in Figure 10.
Model of wind turbine is in wind turbine; models of control system of generator-side inverter and grid-side inverter are included in Subsystem 1 and Subsystem 2. The MPPT controller and PI controller are also included in Subsystem 1 and Subsystem 2. The pitch angle controller is completely modelled in wind turbine. In this simulation, the wind turbine PMSG model obtains the wind speed and provides an optimal reference speed to control the system. The simulation results are shown in Figures 11–14.

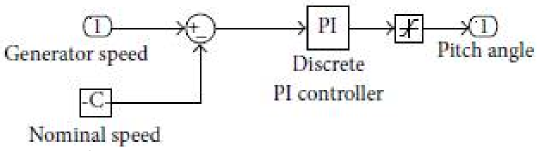

Figure 8:Model of pitch angle controller inMatlab Simulink 2010b.

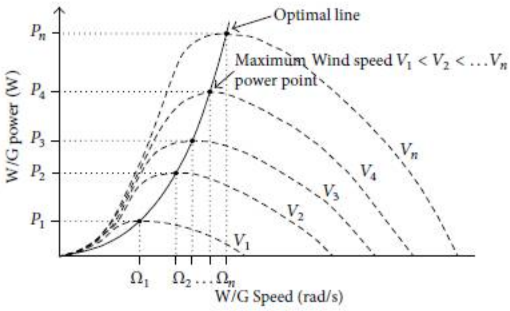

Figure 9: Wind turbine generator power curve at various wind speeds.

Figure 11 shows the waves of DC-link voltage, the voltage is produced by grid-side inverter and A-phase voltage feeding to the grid. Through the results, it is admitted that DCvoltage is well controlled in stabilizing performance with the fluctuation being about 25%. When Vab passes through the inverter, load voltage slightly fluctuates by the late modelling during 0 s to 0.08 s. After that, the load voltage can be kept in stable output.
Figure 12 shows the wave forms of d-current, voltage phase of PMSG, and d-voltage reference. According to the results, it can be revealed that, despite the usual change of wind speed, the d-axis current is still modelled to be maintained at zero level off.
The voltage phase per unit (pu) of PMSG is decreased after the beginning stage; however, it keeps constant value at that later time.
Figure 13 shows the waves of three-phase voltage and current of the grid when autonomous PMSG wind turbine is operated at stable state. Voltage phase almost opposes the current phase.
Figure 14 performs the waves of active power and reactive power decoupling control.When the wind turbine catches the
wind speed at rate 4m/s, PMSG begins to operate. Therefore, the pitch angle is controlled to catch the maximum coefficient at rate 13 m/s wind speed. After 0.14 s, the generator-side inverter and the grid-side inverter are cooperated to control the voltage through controllers. The wind turbine gets the stable output power to the grid with standard voltage, frequency, and phase.
By the autonomous control, including pitch angle controller, generator-side inverter, and grid-side inverter, the wind turbine is able to achieve the highest efficiency. Through the MPPT strategy as well as pitch angle controller, it can catch the maximum wind energy and operate at optimal speed ratio.

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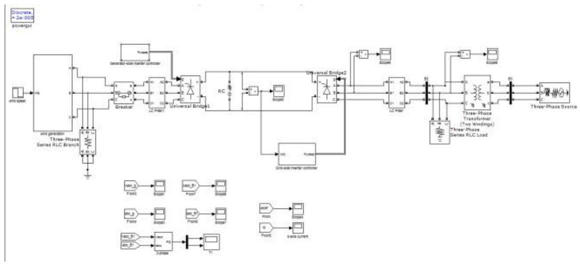

Figure 10: Simulation model of autonomous control PMSG wind turbine.

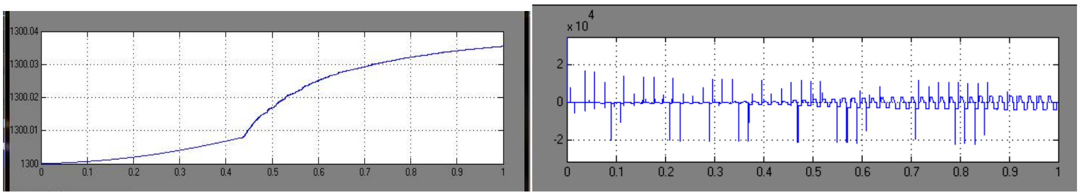

Figure 11: DC-link voltage, load voltage, and inverter voltage.

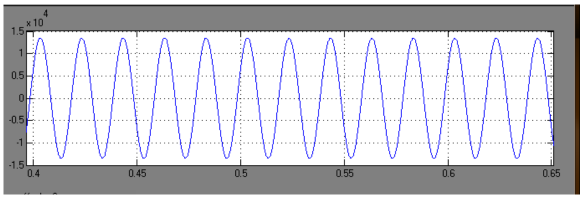

Figure 12:Line-line voltage.

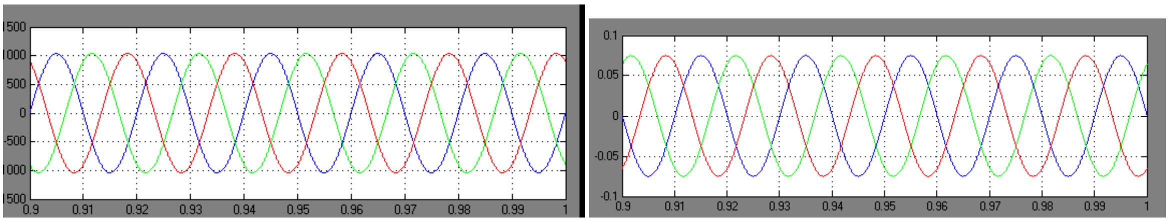

Figure 13:Three-phase voltage and current of the grid.

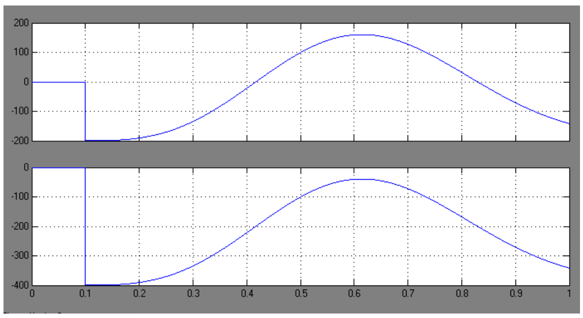

Figure 14: Active and reactive power.

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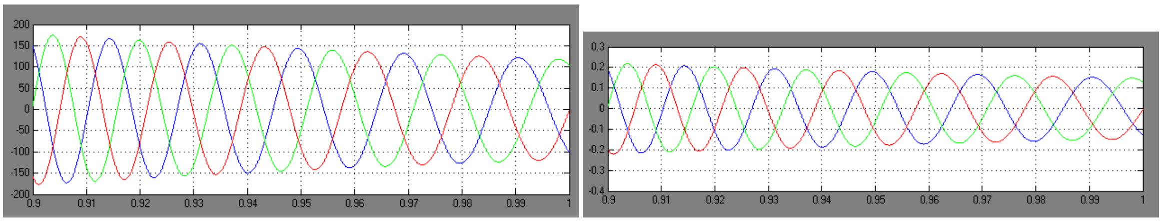

Figure15 Three-phase voltage and current of the wind turbine

V. CONCLUSIONS

This study analyzes the control strategies as well as models and designs and simulates the whole autonomous system of PMSG wind turbine feeding AC power to the utility grid in Matlab Simulink 2010b. The simulation results show that the combination of pitch angle controller, generator-side inverter controller, and grid-side inverter controller has good dynamic and static performance. The maximum power can be tracked and the generator wind turbine can be operated in high efficiency. DC-link voltage is kept at stable level for decoupling control of active and reactive power. Hence, the output will get the optimum power supply for the grid.

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